Possible Origin of the Secondary Stream of Neutral Fluxes at 1 AU

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Abstract. The existence of a secondary stream of neutral atoms inside the heliosphere arriving from about 285° ecliptic longitude, which is about 30° higher than the nominal upstream direction of the inflowing interstellar gas, has been proposed recently based on a wide variety of observations from many different missions. We will discuss the LENA/IMAGE measurements in detail and conclude that the secondary stream is composed mainly of hydrogen atoms at an energy of about 1 keV. We will discuss some possible explanations for the origin of the secondary stream, with the most likely source being the region upstream of the termination shock.

INTRODUCTION

Due to the motion of the heliosphere (HS) through the local interstellar cloud (LIC) at about 25 km/s, interstellar neutral (ISN) gas flows through the heliosphere. The Earth passes near the upwind direction of this flow relative to the Sun about June 5 every year (day 156), when it is near 254˚ ecliptic longitude [1]. Several independent observations for both H and He, including direct neutral gas observations [2], UV backscattering [3], and pickup ions [4], have established this direction along with the resulting spatial distribution and kinematics of the particles. In addition, the derived flow is consistent with UV absorption measurements in the light of nearby stars [5].

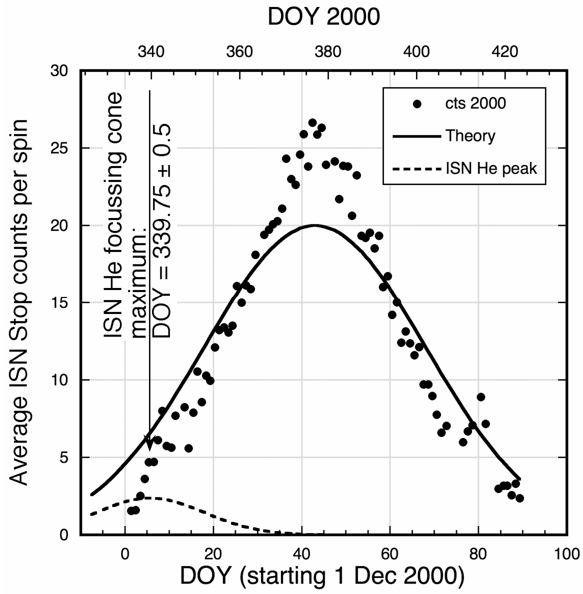

Figure 1: Neutral atom data from IMAGE/LENA at the downwind side (solid circles); theoretical count rate for the He focusing cone signal (dashed line); modeled downwind signal for the secondary flow (full line).

The presence of this well-established ISN influx leads to the expectation that neutral atom (NA) data at 1 AU would be symmetric with respect to the 74˚ / 254˚ ecliptic longitude axis. However, a number of neutral atom data sets at 1 AU curiously are not centered on this axis, but at ecliptic longitudes that are larger by about 10˚–40˚, depending on the data set in question, which was discussed recently

[6]. The origin of this NA flow, which we will refer to as the secondary flow, will be discussed in this paper.

MEASUREMENTS

The first data set we discuss in detail are the NA data from IMAGE/LENA recorded near the downwind direction of the of the ISN flux, which are shown in Fig. 1. As can be seen easily, the NA data does not peak at the time (place in the orbit) where the maximum of the He focusing cone is expected at DOY 339.75±0.5. The expected NA signal for the He focusing cone is given in Fig. 1 as dashed line. The observed NA signal peaks more than 30 days later and is also observed in the succeeding years. Nominally, neutral atoms are detected via negative charging these atoms upon reflection off a suitably designed conversion surface in the LENA instrument [7, 8]. However, these NAs are detected indirectly. The incoming atoms are energetic enough to remove (sputter) a negative ion from the conversion surface during impact, which is what is actually registered, and the information we have on the original particle is only its direction. Interstellar He has barely enough kinetic energy to sputter (the He kinetic energies at the IMAGE orbit range from 75 to 170 eV), hence the expected signal is small (see Fig. 1). By the way, He does not form a stable negative ion. Since the measured NA signal arrives at a later time and is significantly larger than the expected ISN He signal we have to assume a different and more energetic source of neutrals causing it, a secondary flow. Hydrogen is most likely the dominant species in such a flow. To efficiently sputter from a surface its energy has to be about 1 keV or more. These assumptions will be used later for the interpretation.

The second data set we discuss in detail are the neutral solar wind (NSW) data from LENA/IMAGE, which we reported earlier [6]. NSW is flowing in the same direction as the charged solar wind, at about the same energy with an abundance fraction of about 10^{-4} [9]. The NSW data for the years 2000 and 2001 are shown in Fig. 2. The low fluxes early and late in the year is NSW arising from solar wind interacting with dust located along the Earth-Sun line [10]. The dashed line in Fig. 2 gives the expected NSW signal arising from charge exchange of interstellar neutral hydrogen atoms with solar wind protons (see below). The solid curve in Fig. 2 gives a Gaussian fit to the NSW peak indicating a peak flux about 30 days later than the expected maximum due to the

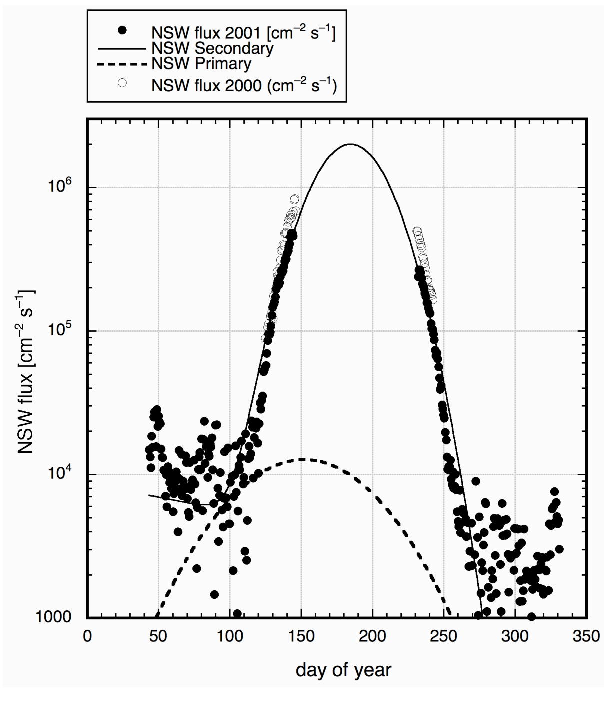

Figure 2: Solid and open circles: NSW data from LENA/IMAGE; Dashed line: NSW resulting from charge exchange with the interstellar gas; solid line: fit to NSW data of 2001. Data are from ref. [6].

ISN inflow. Again, the offset in time (e.g. place in orbit) and the large flux suggest a different, e.g. second, source of neutral gas flow resulting in charge exchange with solar protons. The assumption of hydrogen atoms being the major species in the secondary flow gets additional support here because a resonant charge exchange process (hydrogen with protons) is far more efficient than with different species. The maximum flux of the secondary flow has to be derived from the peak fit, which causes some uncertainty.

ANALYSIS

The inflowing ISN gas becomes ionized, which reduces its density, when approaching the Sun. The relevant processes are charge exchange with the solar wind, photoionization by EUV photons emitted from the Sun, and electron impact ionization by solar wind electrons. For hydrogen mainly charge exchange with the solar wind protons is responsible for the ionization. The density of the inflowing ISN gas at a distance r from the Sun can be written as

$$n_{ISN}(r) = n_0 \exp\left(-\frac{\beta r_1^2}{v_{ISN}\, r} \frac{\phi}{\sin\phi}\right) \tag{1}$$

where β is the ionization rate at 1 AU, n_0 the density of the interstellar gas at the termination shock, v_{ISN} is the speed of the inflowing ISN hydrogen, ϕ is the position of the observer relative to the upstream direction of the ISN gas, and $r_1 = 1AU$ [11]. For simplification we assume in Eq. 1 that the gravitational force balances the photon pressure ($\mu = 1$). The neutral solar wind resulting from the inflow of ISN and the subsequent charge exchange with solar wind protons is given by

$$\Phi_{NSW}^{ISN}(r) = \Phi_{SW}\, \sigma n_0 \frac{v_{ISN}}{\beta} \frac{\sin\phi}{\phi} \exp\left(-\frac{\beta r_1^2}{v_{ISN}\, r} \frac{\phi}{\sin\phi}\right) \tag{2}$$

where $\Phi_{SW} = v_{SW}\, n_{SW} \approx 4 \cdot 10^8\, cm^{-2} s^{-1}$ is the solar wind flux, and $\sigma = 2 \cdot 10^{-15} cm$ is the charge exchange cross section. Using $v_{ISN} = 22\, km/s$ and $n_0 = 0.17\, cm^{-3}$ for hydrogen inside the termination shock we get for the expected NSW flux $\Phi_{NSW}^{ISN} = 1.27 \cdot 10^4\, cm^{-2} s^{-1}$ in the upwind direction ($\phi = 0$). The contribution of this process to the NSW is shown in Fig. 2 as dashed line.

We assume that the large enhancement seen in Fig. 2 is also NSW but arising from charge exchange with a secondary flux of neutral hydrogen, since these NAs arrive from the direction of the Sun as well. Thus we also can write for this flux

$$\tilde{\Phi}_{NSW}^{SF}(r) = \Phi_{SW}\, \sigma \tilde{n}_0 \frac{\tilde{v}_{SF}}{\beta} \frac{\sin\phi}{\phi} \exp\left(-\frac{\beta r_1^2}{\tilde{v}_{SF}\, r} \frac{\phi}{\sin\phi}\right) \tag{3}$$

where, $\tilde{n}_0$, $\tilde{v}_{SF}$, $\tilde{\Phi}_{NSW}^{SF}(r)$ have the same meaning as in Eq. 2 but for the secondary flux (SF) of neutral atoms, with $\tilde{\Phi}_{NSW}^{SF}(1AU) = 2 \cdot 10^6 cm^{-2} s^{-1}$ from the fit given in Fig. 2. Admittedly, the uncertainty of this number is large because the fit has to be done to the feet of the distribution since the peak is out of the field-of-view of LENA/IMAGE. Assuming this secondary flux is dominantly hydrogen atoms (the most likely candidate) and that their velocity is $\tilde{v}_{SF} = 440\, km/s$ (i.e., their energy is about 1 keV) we derive for the density of the secondary flow by inverting Eq. 3:

$$\tilde{n}_0 = \frac{\phi}{\sin\phi}\beta\frac{\tilde{\Phi}^{SF}_{NSW}}{\tilde{v}_{SF}\Phi_{SW}\sigma}\exp\left(\frac{r_1^2}{r}\frac{\beta}{\tilde{v}_{SF}}\frac{\phi}{\sin\phi}\right) \tag{4}$$

Being at Earth orbit ($r = 1AU$) gives for the density of the secondary flow $\tilde{n}_0 = 0.038\,cm^{-3}$, and compared to the ISN gas we obtain $\tilde{n}_0/n_0 = 0.22$.

Since the velocity of the secondary flow is rather high there is hardly any effect of the ionization in the upwind region (Eq. 1) and the shape of the measured distribution (Fig. 2) is a result of the source distribution. Evaluating Eq. 1 for the parameters of the secondary flow we find that in the upwind direction of the secondary flow the neutral fraction arriving at 1 AU is about 83% and on the sides 50° away of the upwind direction the neutral fraction is still 80%. Thus the shape of the secondary flux most likely represents the spatial distribution in longitude of the source of these particles.

The signal of the secondary flow is well characterized by a Gaussian distribution with $\sigma = 23.6^\circ$ and a peak flux $\tilde{\Phi}^{SF}_{NSW}(1AU) = 2\cdot10^6 cm^{-2}s^{-1}$. With this description we can investigate what happens to this flow when it passes the Sun and propagates into the downwind region. To obtain the flux in the downwind region we have to integrate the ionization probability along the particle trajectory, multiplied by the distribution of the source in longitude and the temperature of the source:

$$\tilde{\phi}_{SF}(\phi_0) = \int \exp\left(-\frac{\beta r_1^2}{\tilde{v}_{SF}\, r}\frac{\phi}{\sin\phi}\right)\cdot\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{1}{2}\frac{(\phi-\phi_0)^2}{\sigma^2}\right)\cdot\frac{1}{\Delta\phi_T\sqrt{2\pi}}\exp\left(-\frac{1}{2}\frac{(\phi-\phi_0)^2}{\Delta\phi_T^{\;2}}\right)d\phi \tag{5}$$

where the last term refers to the temperature of the source, which is given by

$$\Delta\phi_T = \arctan\left(\frac{1}{\tilde{v}_{SF}}\sqrt{\frac{2k_B\tilde{T}}{m}}\right) \tag{6}$$

The evaluation of Eq. 5 gives a peak flux at the downwind side of the secondary component of $630 \pm 200\,cm^{-2}s^{-1}$. By applying LENA/IMAGE efficiencies we get a peak signal of $20 \pm 9\,cts/spin$, which is in good agreement with the observed peak signal of $27\,cts/spin$ (see Fig. 1). To get agreement with the observed downwind data the temperature of the source was used as fit parameter and the best agreement between data and calculation was found for a value of $T = (2.5 \pm 0.5)\cdot10^4 K$. Note that the observed downwind distribution of the secondary component (see Fig. 1) cannot be explained by a parallel flow with a high temperature of $T = 2\cdot10^6 K$, which corresponds to the observed width in longitude (see Fig. 2). For that case, the resulting distribution on the downwind side is too different from the observations.

DISCUSSION

Above we have derived some basic properties of the observed secondary flow based on NA observations, together with some assumptions. In the following we shall discuss the possible source(s) of this secondary flow. The stars of the galaxy, the G-cloud, the area between the termination shock and the bow shock of the heliosphere, and a planetary source have been put forward as possible candidates for these NAs. First of all we estimate the distance of the source from our Sun. The mean free path of atoms in the

LIC is of the order of 100 AU. Thus, a flow of energetic atoms moving within the LIC would at some distance equilibrate with the LIC, and be of the same speed and temperature as the LIC. As a crude estimate one would expect the source of the secondary stream to be located within 2000 AU depending on the unperturbed density of the ISN gas far from the HS.

Galactic centre: The observed arrival direction of the secondary flow is commensurate with a NA source in the direction of the Galactic centre (see ref. [6]). Thus, one could imagine that the observed stream of neutral particles is the sum of many neutral stellar winds, similar to the NSW of our Sun [9]. The peak of this flux in the direction of the Galactic centre would arise simply from the large amount of stars in this direction compared to the direction away from the Galactic centre, and our solar system being at the periphery of our galaxy. However, as discussed above, the distance of these sources is much too far away for an NA flow to arrive at our solar system with velocities much faster than the LIC. Thus, we have to exclude the sum of stellar winds as a candidate for the source of the secondary flow.

Shock at G-cloud: The G-cloud is neighboring our LIC in rather close proximity, located approximately in the direction of the Galactic centre [3,12]. It is assumed that there is a gap between the two clouds that is filled with hot but dilute gas. Alternatively, it has been proposed that the two clouds are in contact and that a weak shock has formed in the interaction region [13]. In the shock region ions will get energized and some of these ions will become energetic neutral atoms. Since the observed direction of the secondary stream is approximately the direction to the G-cloud this shock may be its source. However, the distance to the G-cloud is approximately 30'000 AU [13], which is too far so these neutral atoms will have equilibrated with the LIC. This argument, together with the uncertainty about the existence of a shock between the two clouds, makes it rather unlikely that this is the source of the secondary flow.

Termination Shock: The termination shock (TS) is thought to be at a distance of about 100 AU from the Sun in the upwind direction, and further out is the bow shock at about 250 AU (if it exists). In front of the heliopause ISN hydrogen and oxygen are piled-up, which is known as the hydrogen wall [14]. Also, the area around the TS is the place where ion acceleration will take place. For example, the anomalous cosmic rays are believed to originate from this area [15]. Since there is a co-existence of neutral gas and ions there will be charge exchange between the species and neutral energetic atoms will leave this area. There is even a dedicated mission under investigation to record the energetic atoms originating from the vicinity of the TS [16]. One last thought is that the position of the TS is given by the pressure balance between the flows of interstellar gas and the solar wind, to first order. If the secondary flow would arrive from outside the bow shock, it would exert a pressure on the HS that is almost 100 times larger than the pressure of the ISN flow and the TS would be much further inside the solar system, at distances where it should have been observed already. Therefore, we conclude that origin of the secondary flow is at the TS and in its vicinity. However, one would still expect the secondary flow to be aligned with the inflow of the ISN. Perhaps the observed offset in longitude can be explained by the existence of an interstellar magnetic field that distorts the HS and the associated hydrogen wall [17].

Planetary Source: The source of the secondary flow could also be further inside our HS. It is well known that the charge exchange processes around planets between magnetospheric particles and neutral atmospheric particles give rise the emission of energetic neutral atoms. Jupiter, for example with its large magnetosphere would be a prime candidate for such a source. However, planetary sources move with time, which is not observed in the LENA/IMAGE data. Therefore we have to rule out planetary magnetospheres as a source for the secondary flow.

CONCLUSIONS

We have presented the arguments for the interpretation of a stream of energetic atoms coming from the direction of about 285° in ecliptic longitude. The stream is assumed to be composed of mainly of neutral hydrogen atoms, with a speed of about 440 km/s and a density of 0.038 cm^{-3}. We conclude that the observations of this secondary flow can be best explained by the energetic neutral atoms originating from the area upstream of the termination shock.

The ASPERA-3 instrument on the Mars Express mission of the European Space Agency (ESA) has a neutral particle sensor in the proper energy range (100 eV – 10 keV) [18]. This instrument will allow the direct detection of this secondary flow if the flux and the velocity estimated above are correct. If it turns out that ASPERA's geometric factor is too small there is still hope. At this writing, the IBEX mission is currently under evaluation for possible selection for the next SMEX mission opportunity of NASA [16]. In a few years from now we will know much more about this secondary flow of neutral particles.

REFERENCES

1 P. C. Frisch, *Am. Sci.* 88 (Jan.-Feb.), 52 (2000).
2 M. Witte, M. Babaszkiewicz, and H. Rosenbauer, *Space Sci. Rev.* 78, 289–296 (1996).
3 R. Lallement, *Space Sci. Rev.* 78, 361 (1996).
4 G. Gloeckler and J. Geiss, *Space Sci. Rev.* 97, 169 (2001).
5 P. Bertin, R. Lallement, R. Ferlet et al., *Jou. Geophys. Res.* 98, 15193 (1993).
6 M.R. Collier, T.E. Moore, D. Simpson et al., *Adv. Space Science*, in press (2004).
7 P. Wurz, M.R. Aellig, P. Bochsler et al., *Opt. Eng.* 34, 2365–2376 (1995).
8 T.E. Moore, D. Chornay, M.R. Collier et al., *Space. Sci. Rev.* 91, 155–195 (2000).
9 M.R. Collier, T.E. Moore, K.W. Ogilvie et al., *Jou. Geophys. Res.* 106 (A11), 24893 (2001).
10 M.R. Collier, T.E. Moore, K. Ogilvie et al., Solar Wind X, *AIP* 679, 790, (2003).
11 V.M. Vasyliunas and G.L. Siscoe, *Jou. Geophys. Res.* 81, 1247 (1976).
12 R. Lallement and P. Bertin, *Astron. Astrophys.* 266, 479 (1992).
13 S. Grzedzielski and R. Lallement, *Space Sci. Rev.* 78, 247 (1996).
14 J.L. Linsky and B.E. Wood, *Astrophys. Jou.* 463, 254 (1996).
15 G. Gloeckler and K.P. Wenzel, in *The Century of Space Science*, edited by J.A.M. Bleeker, J. Geiss, and M.C.E. Huber (Kluwer Academic Publishers, 2001), Vol. II, pp. 963.
16 D.J. McComas, F. Allegrini, P. Bochsler et al., these proceedings (2004).
17 R. Ratkiewicz, A. Barnes, G. A. Molvik et al., *Astron. Astrophys.* 335, 363 (1998).
18 S. Barabash, R. Lundin, H. Andersson et al., *ESA-SP*, in press (2004).